Design of a Compact High-Temperature Gas Heater for a VHTR Simulated Loop

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1. Introduction

A small scale gas loop that can simulate a VHTR (Very High Temperature Gas Cooled Reactor) is now under development at the Korea Atomic Energy Research Institute [1]. A high-temperature heater is a key component of a gas loop. The heater should be operated at a temperature up to 950 °C and at a pressure up to 6MPa. Non-metal heater elements like a graphite, a C/C composite, a SiC or a Kanthal are used as the heater elements of the high-temperature heater because they can withstand a temperature over 1600°C. In this study, we discussed the design methodology of a Compact High-Temperature Heater (CHTH) that has the following operating condition;

Pressure,	4-6 MPa
Inlet/outlet temperature,	500/1000 °C
Flow rate,	0.034 kg/s

In addition, we carried out the design analyses for obtaining the mechanical and T/H requirements of the CHTH.

2. Design analyses

2.1 T/H Requirements

The heat transfer in a turbulence flow is one order larger than the heat transfer in a laminar flow, the primary T/H requirement of the CHTH is maintaining the channel flow “turbulence.” The requirement of the Reynolds to be turbulent is,

$$\mathrm{Re} = \frac{\rho \upsilon D_h}{\mu} > 2300.$$

For a fully developed turbulent flow, Dittus and Boelter heat transfer relation [2] is as follows;

$$Nu_d = 0.023 \mathrm{Re}_d^{0.8} \mathrm{Pr}^{0.4}. \qquad (1)$$

The maximum operating temperature of the heater elements can be limited by the allowable temperatures of an internal insulator, a reflector and a heater element itself. The super Kaowool insulator has a lower temperature limit of 1650°C than others. CHTH is provided with an internal thermal insulator to protect the pressure vessel from the high-temperature gas.

If we assume the maximum-outer-surface-temperature of the pressure vessel, we can obtained the minimum thickness of the internal insulator with the following energy balance

Heat transfer through conduction
= Heat loss through convection and radiation.

2.2 Mechanical Requirements

Three aspects of the mechanical design analysis of a CHTH are considered to establish the mechanical requirements; fluid-induced vibration, sound-induced vibration, and thermal stress analysis. The fluid induced vibration (FIV) is the result of a gas impinging on the heater elements. The flow can cause a vibration that can damage a flexible structure. The reduced velocity for the onset of a whirling instability is [3],

$$\frac{U_{Critical}}{fD} = K\sqrt{2\pi\zeta \frac{m}{\rho D^2}}. \qquad (2)$$

The sources of an acoustic vibration (AV) are a series of interconnected ducts and cavities. The speed of sound in a gas at a relatively low pressure and high temperature varies with the square root of the temperature [3];

$$\upsilon_S = \sqrt{\frac{\gamma \Re T}{M}}, \qquad (3)$$

Thermal stresses are induced in any restrained components by the tendency of materials to expand as they are heated by a high-temperature gas. Thermal stresses which are generated as components attempt to expand against restraints provided by adjacent structural supports. Below 450°C, creep and creep rupture effects are usually negligible in the steels and nickel-chromium-iron alloys used in a VHTR.

3. Results and discussions

Figure 1 shows various candidates of the CTHT heater array. As we can see from the calculation results listed in Table 1, Reynolds number is decreased with the number of array increased. 2x2 array has a fully turbulence flow of Re = 6251. Figure 2 shows the CHTH layout and its major parts. The pressure vessel of the main heater is internally insulated to protect the pressure vessel from the high-temperature gas. The liner also has a function of a reflector against a thermal radiation being emitted by the heater elements. Heater array goes through a large radiation heat loss when operating at a high temperature. A reflector reduces the radiation loss; it reduces heat loss of the CHTH. Although the insulator material has a good thermal conductivity itself (Kaowool, has the conductivity of 0.2 W/mK), the effective thermal conductivity of the internal insulation kit is doubled when compared to the bare Kaowool insulator due to the additional heat transfer through the metal supports of the internal liner or plates and a permeation of the gas into the porous insulator. The graphite or C/C composite heater element is a proper choice as the CHTH element because it can withstand over 2000 °C in an oxygen free environment. In the case of a direct current heating method, the heater elements should be electrically insulated. A BN-P ceramic spacer is being designed to give this function and it will be installed at the inner and outer part of the 2x2 array.

The requirements to prevent the CHTH from FIV and AV are obtained by equation (2) and (3). The design specifications of the CHTH are derived from the requirements of the nitrogen gas (Table 2).

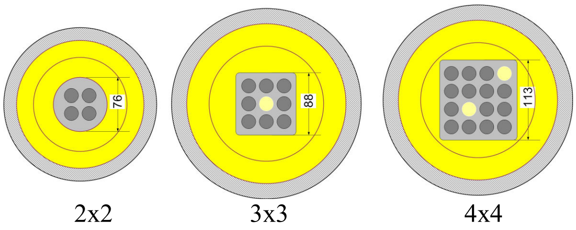

Figure 1. Layouts of the Flow Channels in CHTH

Table 1. Major T/H Parameters of the Heater Array

Parameter	2X2	3X3	4X4
Operating Condition	P=40bar, T=1200K, W=0.034kg/s		
Flow area (m^2)	0.0033	0.0049	0.00774
Velocity (m/s)	0.9	0.6	0.4
Reynolds Number	6251	4210	2665
HT Coef., h (W/m^2K)	59	43	30

Table 2. Design Requirements of CHTH

Item	Design Requirement
FIV	$U/(fD)$ < 8.4 for N_2 (22 for He)
AV	U << 309m/s for N_2 (1739m/s for He)
Insulator	- Operating T > 1500 °C - Thickness (Kaowool) > 27 mm
Heater Internal	- Heater outlet T ≥ 1000 °C - Heater maximum T < 1500 °C - Reynolds number >> 2300 - Liner Retain Reflection
Vessel	- outer surface T Alloy << 450 °C - outer surface T Sus 316 < 360 °C

4. Conclusions

We designed a Compact High-Temperature Heater for a VHTR simulated gas loop. We established the following results for designing the CHTH;

1. The primary concern of the mechanical design is to prevent the thermal stress of the CHTH parts.

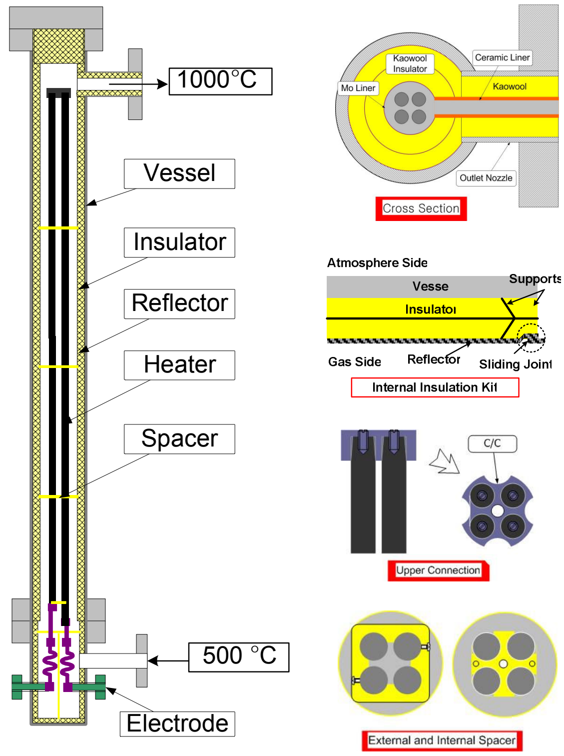

Figure 2. CHTH Layout and Major Parts

2. Internal insulator kits should be equipped in the CHTH. While a careful design of internal insulator can overcome the loop failure at a hot location, the size of the outer pressure vessel is increased.
3. The effective thermal conductivity of an internal insulation kit is greater than a bare insulator
4. Radiation heat loss is degrading the CHTH performance. Reflector should be installed.

ACKNOWLEDGEMENTS

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